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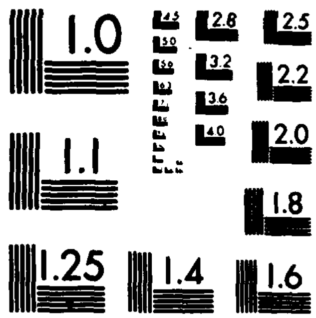
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FOREIGN TECHNOLOGY DIVISION

PROBLEMS OF BUILDING TURBOGENERATORS WITH WINDINGS
MADE OF SUPERCONDUCTORS AND PURE METALS

by

G.G. Schastlivyy, G.M. Fedorenko, et al

EDITED TRANSLATION

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О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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PROBLEMS OF BUILDING TURBOGENERATORS WITH WINDINGS MADE OF SUPERCONDUCTORS AND PURE METALS

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The increase of the unit power of the machines and the power plant as a whole is a characteristic feature of the development of turbogenerator building. With the rapid growth of power systems, this is caused by the need for reducing the capital outlays and construction times, decreasing the operating expenditures, and increasing the efficiency of the installations.

The unit power of turbogenerators is doubled every 7-10 years in industrially developed countries. Assemblies with a unit power of 800-1200 MW have already been built or are being built today. With such a high rate of development, we can assume that in the near future, the unit power of the installations will increase to 2-5 million kW. An increase in the unit power such as this must mainly occur by the further intensification of the electromagnetic loads, since the increase in the dimensions is limited by the maximum mechanical stresses and transportation capabilities. In this case, increasing the electromagnetic loads in conventional turbogenerators leads to a considerable increase in the losses.

The use of superconductors and pure metals with cryogenic cooling opens new possibilities for progress in the manufacture of large electric machines.

The use of these materials makes it possible to increase the current density in the windings by 1-2 orders of magnitude, and the induction in the gap - 5-10 times, without significant losses of electric power.

The general technicoeconomic basis for using superconductors and pure metals in electrical machines is given with ample thoroughness in Soviet and foreign literature [1, 4, 10, etc.], where the basic characteristics and problems related to the creation of these machines are also discussed. These characteristics and problems are primarily determined by the use of superlow temperatures (4-20°K) for cooling the windings and a considerable increase in the electromagnetic loads. It turns out to be more economically advantageous to use deep cooling than ordinary cooling when

$$\frac{P_x + N_x}{P_N} = \frac{P_x}{P_N}\left(1 + \frac{T - T}{T\eta}\right) < 1.$$

where P_x are the losses which occur at a low temperature; N_x are the power expenditures of the cooling plant; P_N are the losses in a winding with normal cooling; $\frac{T}{T_0 - T}$ is the efficiency of Carnot's cycle; η is the relative efficiency of a real cooling plant.

The dependence $\frac{P_x + N_x}{P_N} = f(T)$, which was found for different metals [10], makes it possible to detect a very distinct minimum, which is located in the range of the liquefaction temperature of hydrogen or neon for copper $Cu_{99.994}$ and aluminum $Al_{99.999}$. At this temperature, $\frac{P_x + N_x}{P_N} = 0.2\text{-}0.25$, which makes it possible to double the power of the machine. The heat influx from the outside is disregarded when considering this dependence, since compared to the losses in the winding, it does not play a significant part at a temperature of 20°K. When superconductors are used, there are no losses in the windings, which are located in a constant magnetic field, and the power losses of the cooling plant are only spent on covering the heat influx from the outside.

Since a superconductor winding must be at a temperature close to 4.2°K, this heat influx increases considerably, while the expenditures

on removing 1 W from a temperature level of 4.2°K become an order of magnitude greater than the expenditures on removing 1 W from the space at 20°K. All of this has a considerable effect on the economic effectiveness of using superconductors in the windings of electric power machines. However, the problem of using superconductors in fixed direct-current windings can be considered to be solved at present. The IRD organization (Great Britain) has built a unipolar superconducting disk-type motor with a nominal power of $P = 2400$ kW; $n = 200$ rpm; $I = 5800$ A; $U = 430$ V; $\Phi = 6.45$ Wb [11]. At 200 rpm, a superconducting electric motor can be created with a nominal power of up to 40,000 kW, whereas for ordinary direct-current electric machines, the maximum attainable power at this rotation rate is approximately 10,000 kW. A motor with a superconducting excitation winding weighs 30 t. A conventional motor with this power is three times as large and weighs 300 t.

Rigid superconductors of the type Nb_3Sn or NbTi in an alternating magnetic field have great losses, which are proportional to the frequency. Therefore, the use of superconductors in turbogenerators is limited only by the excitation winding.

The creation of the optimum design of a turbogenerator with a rotating superconducting excitation winding is an extremely complex problem which requires in-depth theoretical developments and careful experimental investigations. Here the main problem is creating a rotating cryostat which provides the minimum heat influx into the low-temperature part with the necessary mechanical strength and rigidity of the system.

A design which is one of the possible prototypes of the rotor design of powerful turbogenerators with a superconducting excitation winding was proposed in report [3]. Based on this design, a model of a turbogenerator with a design power of 200 kW was developed and is presently being built at the NII [Scientific Research Institute] of the plant "Elektrotyazhmash."

The load-carrying part of the rotor (Fig. 1) of this model is

a nonmagnetic hollow cylinder 6, which is connected on the ends to the trunnions of shaft 9 through heat-insulating sections 3, which were selected based on the condition of having the full strength of a solid shaft. The material of which the heat-insulating sections are made provides a possible maximum resistance of $\frac{\sigma}{\lambda}$, where σ is the mechanical strength, and λ is the heat conductivity coefficient. The design also provides for using a coolant evaporating in the low-temperature region to cool these sections. All of this provides the minimum heat influx on the heat-insulating sections. The outer surface of the cylinder is surrounded by a vacuum jacket 5, which serves as effective heat insulation irregardless of the action of centrifugal forces. Inside the vacuum jacket, there is heat screen 4, made of a material with high heat conductivity and used to protect the low-temperature container from the heat influx from radiation. The outer shell 1 of the vacuum jacket is made of a material with high electrical conductivity and serves simultaneously as an electromagnetic screen which protects the superconducting excitation winding 7 from the alternating magnetic fields caused by the asymmetry of the load and the higher harmonic reactions of the armature. The losses liberated in the screen are withdrawn by gaseous helium which exits from the rotor through gap 2. From the ends, the low-temperature volume with the excitation winding which it houses is protected from the heat influx by vacuum plugs 10. The superconducting excitation winding is fastened on frame 8.

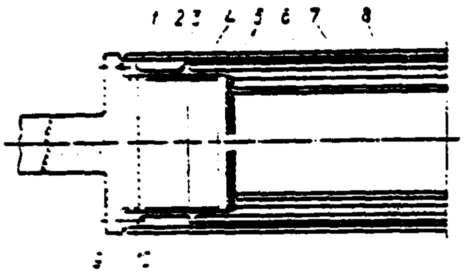

Fig. 1.

The published results of studies conducted abroad and involving the use of superconductors in the rotating excitation winding of turbogenerators confirm the validity of the design decisions made. Reports [6-8] discuss conducting studies on an experimental machine with a rotating superconducting (SC) [SP] excitation winding. It is a two-pole generator operating at 3600 rpm designed for 80 kVA, 450 A.

The main purpose of the study was to prove the possibility of

building a rotating cryostat with a SC excitation winding located inside it. Experiments with short circuiting under working conditions, during idling, and with reduced voltage were conducted. The studies showed that a rotating SC excitation winding can operate successfully in a synchronous generator.

The results of tests of the generator designed for 80 kVA served as the basis for creating the plan for a cryoturbogenerator with power of 1000 mW [8, 9]. The mean value of the current density in the SC excitation winding was considered to be 124 A/mm^2 with maximum inductance of 5.5 T.

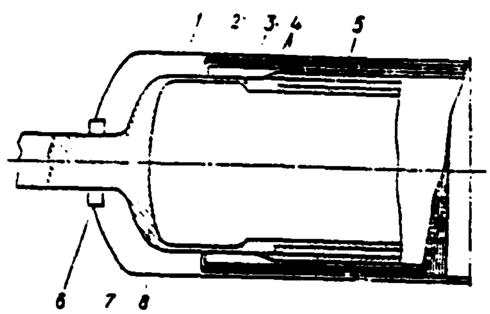

Fig. 2.

The schematic diagram of the rotor (Fig. 2) makes it possible to state that this design is very similar to that proposed in [3]. In both cases, the rotor is a nonmagnetic cylinder 3 connected with the trunnions of shaft 8 by heat-insulating sections 1. The low-temperature volume with the SC excitation winding 5 located inside it is cooled by liquid helium and surrounded by vacuum jacket 4. Both designs have an electro-thermal screen 2 which rotates along with the rotor. However, there are certain differences.

In the design of the rotor according to report [3], the electromagnetic and heat screens are on different temperature levels: the first - at a normal temperature, and the second - at a temperature of 77°K. According to report [9], the functions of these screens are combined, and the combination screen is at a temperature of 20°K. The vacuum jacket around the rotor [9] is made with a vacuum seal onto shaft 6, since its upper jacket 7 is fixed. Considering the large diameter of the driven shaft, which transfers the 1000 mW of power, the rotation rate - 3600 rpm, and the vacuum (at least 10^{-5} mm Hg) which is necessary for efficient heat insulation, it is difficult to make this seal. In the design according to [3], the vacuum-sealed container rotates along with the rotor; in this case, the high vacuum

is provided by welding together the electromagnetic screen and the carrying cylinder and using an adsorbent. The design of the end sections of the rotor is also somewhat different, since in the design according to [8], the complete use of the gaseous helium coming from the cryostat is not provided for cooling the heat-insulating sections, and it is considered that the main heat influxes will be absorbed by the electrothermal screen.

From the comparison given we can outline the general form of a rotating cryostat with a superconducting excitation winding placed inside of it. However, the design of its individual assemblies can differ greatly. Here special attention should be given to the mechanical calculation of the rotor versions under consideration.

Cryogenic liquid	Critical heat influx, W/cm^2	Temperature gradient, deg
He	0.8	0.6
H_2	9.0	3.0
N_2	19.0	12.0

Besides minimizing the heat flow into the rotating cryostat, providing thermal stability of the winding during deep cooling is also a complex problem; in the final analysis, this is what determines the overload capacity of the electric cryomachine. Windings with superconductivity can be cooled by liquid or gaseous helium. Cooling with a boiling liquid gas, when the heat of vaporization is used, is considered to be the most efficient. In this case, the difference in the temperatures of the winding and the cooling medium is very small as long as the critical heat flux per unit of surface area is not exceeded.

The table gives the critical heat fluxes during nucleate boiling and the temperature gradients between the cooled surface and the cryogenic liquid in a large volume at a pressure of 1 at [10].

The specific heat capacity of superconductors becomes very small at low temperatures. For this reason, the winding cannot accumulate heat during overloads, liberating it into the cooling medium when possible. Although the convective heat transfer coefficient of boiling

coolants is rather large, this results in a small value of the heating time constant. Therefore, the winding temperature is immediately established with any load, so that the losses liberated in the winding and the heat which comes from the outside are in equilibrium with the cold productivity of the cooling medium. It follows from the above discussion that the thermal stability of cooling the winding of a cryomachine is lower than that of a normally cooled machine, and it is provided with the condition $\frac{dq}{dT} > \frac{dP_t}{dT}$.

If a winding is cooled by a gas alone, the winding immediately heats up during overloads. Thus, because of the significantly lower heat capacity of the gas, a gas-cooled winding has a lower overload capacity than one cooled with a boiling liquid gas. The thermal stability and, consequently, also the overload capacity of a winding can be increased by increasing the volume of coolant in the winding space, achieving the maximum possible convective heat transfer coefficient, and increasing the effective productivity of the cooling plant. There are few studies of convective heat transfer in cryogenic liquids, and those available were mainly conducted on the surfaces of the simplest bodies (plane, cylinder) and require careful development.

Because of the insufficient dielectric properties of helium, it is very important to create electrical insulation which could be used successfully under conditions of cryogenic cooling and large mechanical loads.

The stator winding of cryoturbogenerators can be made with both ordinary and cryogenic cooling. The presence of a superconducting excitation winding makes it possible to obtain a working induction on the order of 4-5 T, which makes it possible to have a toothless stator with an armature winding located in the gap. The magnitudes of the forces acting on the stator winding increase approximately in proportion to the square of the linear load of the stator. In turbogenerators with direct cooling of the windings, the amplitude value of the force acting on the grooved part of the rod reaches 10 N, and under emergency conditions - 700 N. Smaller forces act on the frontal

part of the stator winding than on the grooved part. Nevertheless, during short circuits in powerful turbogenerators, the tangential component of the force acting on the frontal part reaches 200 N [5]. These forces operate in turbogenerators with a linear load of 1600--2200 A/cm. In cryoturbogenerators with power of 1500-2000 MW, the linear load increases 2-2.5-fold, and the electrodynamic forces acting on the winding are increased 4-6-fold in this case under normal operating conditions. All of this makes the problem of the stability of cryoturbogenerator windings to the action of electrodynamic forces especially urgent.

The absence of magnetic conductors in the working area of the machine and the great increase in the linear loads result in considerable intensification of the leakage fields, which, in turn, leads to an increase in the losses in the conducting design elements. This makes it necessary to carefully study methods of decreasing the leakage fields and the losses they cause, as well as to search for the optimum systems for cooling design elements of cryoturbogenerators.

In view of the extreme change in the electrical parameters of the windings of cryoturbogenerators and the flywheel moment of the rotor, careful studies of the transitional operating conditions are needed, as well as of problems of the static and dynamic stability of the machines.

Thus, we can conclude that the creation of powerful cryoturbogenerators in the near future is a completely feasible problem. However, the problem of creating the optimum design of turbogenerators with a superconducting excitation winding is extremely complex and will require in-depth theoretical developments and careful experimental investigations.

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